Additive manufacturing of soft magnetic material for satellite actuators

Executive Summary Report

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1. BACKGROUND

Soft magnetic materials are used for the production of electromagnetic parts, i.e., magnetic torquers, magnetic shields, electric motors and magnetic bearing parts.

Consequently, soft magnetic materials are essential for satellite mechanisms and satellite subsystems. Soft magnetic materials which can be used for the above-mentioned parts are nickel iron alloys.

Although additive manufacturing (AM) has become an interesting alternative to conventional manufacturing processes for a variety of applications in recent years, research, development, and application of AM technologies has mainly been focused on structural components. While a growing number of materials for structural applications has been examined and qualified for AM processing, functional materials have not been in the focus of AM development. However, the advantages of AM technologies, mainly the ability to realise more complex and optimized designs with reduced material consumption also apply to functional materials.

One of the major drawbacks of using soft magnetic materials is their high density of 8-9 g/cm^3 which is three times heavier than aluminium. Therefore, as minimal as possible of the material shall be used to ensure low system mass. Traditionally, the design options for soft magnetic components are limited because milling and turning are challenging. For this reason, only simple geometries can be realized with conventional manufacturing technologies.

The best results of additive manufacturing of nickel iron material so far were obtained by Laser Powder Bed Fusion (LPBF). Hence, the LPBF process of nickel iron material was established in the frame of this activity. Furthermore, the application of this material processed by LPBF for satellite parts was demonstrated within the activity.

2. OBJECTIVES

The objectives were to reach a part density over 99.5%, a tensile strength above 365 MPa and improvement of magnetic material properties.

For the demonstrator the objective was to develop a rotor for a magnetic bearing with minimum mass. Therefore, manufacturing of complex design elements which are more light weight like lattice structures were a further objective of the activity.

3. METHODS / PROGRAMME OF WORK

To ensure good processability of the powder, a powder specification was developed at the beginning of the activity. Within this document, the required chemical composition, the particle size distribution, the density and the testing methods which shall be used for analysis of those features were defined. After a thorough review of the suppliers for powder feedstock material for LPBF, quotations for the NiFe Powder were requested from selected suppliers. The powder specification was used as baseline for the request for quotation. After evaluation of the quotations a trade-off of the suppliers was performed. Supplier selection was done based on the outcome of the trade-off in agreement with ESA. Subsequently, the powder was ordered. Besides the tests conducted at the Supplier for the Certificate of Conformance (CoC) a feedstock validation was performed at IFAM for a validation of powder quality.

Simultaneously, the state of the art of LPBF of Ni50Fe was studied and summarized in a technical note. Subsequently, space applications and corresponding requirements for the demonstrator were developed. The results were presented to ESA at the MRR0, where a rotor for a magnetic bearing was selected as demonstrator for the activity.

A parameter study was performed, which consisted of two build jobs. The process parameter window was defined based on the state-of-the art and expertise of the consortium. Afterwards, a geometrical study and material characterization including analysis of magnetic and static mechanical properties were performed. In the frame of the material characterization, cantilever geometries were built to calibrate the built simulation. In addition, a threshold temperature was defined to avoid overheating. The results of the geometric limits study were considered in the design of a demonstrator. For development of the demonstrator design mechanical and magnetic simulation was performed. The results of the material characterization were used as input for the simulations. Furthermore, the built of the demonstrator including density cubes, tensile bars and rings as witness samples were simulated thermally and mechanically. To avoid overheating, ghost parts were included in the built. These were calculated based on the calibration performed as part of the material characterization and the defined threshold temperature.

Demonstrators were built by LPBF and mechanically post processed, including blasting and turning of the interfaces to obtain required surface quality. For achievement of final magnetic properties, the demonstrators were heat treated. Density of the demonstrators and witness samples were measured by Archimedean method. Furthermore, X-ray CT and initial magnetization curves of the ring samples from the demonstrator build jobs were recorded. To demonstrate the functionality of the rotor, the magnetic stray field was measured in a Helmholtz setup.

4. KEY RESULTS

The process parameter window where high density was achieved is quite broad. Density above 99% can be obtained with energy densities between 273 J/mm³ and 333 J/mm³. However, best results, that means part density of nearly 100% in the inner volume, were obtained with laser power of 200 W and scanning speed of 550 mm/s resulting in an energy density of 303 J/mm³.

The results of the geometric limits study are summarized in Table 4-1.

Table 4-1 Geometric limits of LPBF process for Ni50Fe50 alloy

Output	Parameter	Comment
Beam compensation	100 µm	Good dimensional accuracy, Small structures can be resolved
Contour vector	0.18 J/mm (100 W, 550 mm/s)	Good contour quality, Minimal protruding edges
Overhang/ downskin vector	0.18 J/mm (100 W, 550 mm/s)	Good surface quality

Minimum distance	200 µm	Reliable separation
Minimum wall thickness	500 µm	Reliable density
Maximum hole diameter	4 mm	No powder bed irregularities
Maximum overhang angle	45°	Sufficient surface quality
Support structures	0.09 J/mm (100 W, 1100 mm/s)	Conical 2 mm branches, 0.3 mm connection points, 0.5 mm trunk
Lattice structure rod diameter	0.5 mm	Reliable structure quality
Tensile specimen type	DIN 50125 type A 4 x 20	Tensile testing possible

A tensile strength of ~500 MPa was achieved in the frame of the material characterization.

Maximum permeability μ_{Max} is over 45000 for the horizontal ring samples of the material characterization. As to be expected the vertical ring samples show a lower maximum permeability of 30000.

Compared to the maximum permeability of previous studies of Ni50Fe50 alloy processed by LPBF, where μ_{Max} was around 7000 the here achieved results are significantly higher. But maximum permeability of the PERMENORM 5000V5 material from VAC is with 135000 three times higher than the one of horizontal ring samples.

Compared to the ring samples with an average density of 98.32 % from previous studies, the here achieved soft magnetic properties are higher, showing a significant lower coercivity, higher permeability, but also slightly higher saturation flux density. Coercivity is at least 567 mA/cm lower, compared to the coercivity measured in previous studies, for all orientations. It was also found that the magnetic properties within each sample orientation show high repeatability. Magnetic properties differ depending on orientation of the samples. The horizontal ring samples show even lower coercivity than the vertical ring samples. Nevertheless, coercivity is still three times higher than specified in the VAC datasheet for PERMENORM 5000V5, which is the primary material used for powder production, although this material is manufactured with another process (not AM). However, the geometry of the demonstrator supports guidance of magnetic stray field as intended.

5. CONCLUSION

The goals to improve mechanical and magnetic material properties for soft magnetic Ni50Fe50 specimens processed by LPBF was achieved. Tensile strength is with ~500 MPa higher than the targeted 365 MPa and close to values of conventionally processed material. Whereas, magnetic properties measured are still lower than those specified in the datasheet of PERMENORM 5000V5 material by VAC. Since the density achieved is already close to 100% it can be concluded that not only density has a strong influence on the magnetic properties.